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ON THE ROLE OF WORKING MEMORY IN RESPONSE INTERFERENCE[1,2]

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Summary.—A recent study by de Fockert, *et al.* claimed that working memory and selective attention are interacting cognitive systems. We used a dual task design that closely resembled de Fockert, *et al.*'s experiment, but using different stimuli. Our subjects first had to store the positions and sequence of a number of blocks. During storage they then had to respond to a few selective attention trials, after which memory was tested. Selective attention was tested using a computerized version of the color Stroop task and the Simon task. We expected to find a monotonic increase of response interference with increasing working memory load, but we found only modest evidence of an influence of working memory on attention. The results shed new light on the nature of and the relation between these cognitive systems.

Two important concepts in experimental psychology are selective attention and working memory. Working memory allows us to store and manipulate a certain amount of information. Thanks to working memory we can integrate information from our surroundings with information stored in long-term memory and adjust our behaviour accordingly (see Baddeley, 1986, for an influential theory of working memory). Selective attention is a system that selects task-relevant input (visual, auditory, etc.) from the environment and hence reduces the load on the information-processing system. Both the working memory and the selective attention systems, however, have their limitations. Information in working memory can only be maintained for a brief period of time, after which it 'decays' or is replaced by other information. There is also a limit on the amount of information that can be maintained (e.g., Smith & Jonides, 1998). The selective attention system has limited filtering capacity because sometimes task-irrelevant information is still processed and may interfere with information processing, e.g., the Stroop phenomenon (Stroop, 1935). Working memory and selective attention are under constant investigation from experimental psychologists, but only recently has the interaction between the systems begun to receive interest. It is often (implicitly) assumed that working memory lies upstream of and receives information from the processing modality after the information has been gated by

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the selective attention system. However, there is some evidence, to be reviewed below, that these systems are not completely independent. The main aim of this study was to seek empirical support for the notion that information in working memory dictates the workings of the selective attention system, in that working memory can influence processing of task-irrelevant information. A second, and closely related aim, is to study whether the act of suppressing task-irrelevant information itself demands working memory capacity.

As a recent example of the interaction of working memory and selective attention, Downing (2000) showed that visual working memory can influence the selective attention system. In that study, subjects had to memorize a face, after which two faces (one of which was the memorized face) were shown on a screen. This was followed by a discrimination stimulus, which was shown either on the position of the memorized face or on the position of the novel face. Reaction time (RT) was faster when the stimulus was shown on the memorized face, relative to the novel one. This finding suggests that the contents of working memory (the face) controls the movements of visual selective attention (for a review, see Awh & Jonides, 2001).

As another example, de Fockert, Rees, Frith, and Lavie (2001) found evidence for a direct causal role for working memory in the control of selective attention, using both behavioral measures and brain imaging (fMRI) data. Put simply, they proposed that working memory is needed to minimize the influence of irrelevant information on further processing. In the present study further evidence was sought for this thesis. We first describe the de Fockert, *et al.* experiment (2001) in more detail. In that study, subjects performed a dual task, wherein they performed a selective attention task and a working-memory task simultaneously. The main research question was to what extent subjects would be able to perform a selective attention task when items were temporarily stored in working memory. The selective attention task required subjects to classify printed names as either pop stars or politicians. The names were printed on pictures of to-be-ignored faces (task-irrelevant information) that were either congruent or incongruent with the names. It was hypothesized that RT would be faster in the congruent condition than the incongruent condition. The RT difference is an index for the strength of the interference effect, which arises due to the response conflict between a name and an (incongruent) face. The working memory task required subjects to store a sequence of five digits that was either in ascending order (0 1 2 3 4) or in a random order, e.g., 2 3 1 0 4. It was expected that the random order would put a greater load on working memory than the ascending order.

In the experiment, these two tasks were combined. Subjects were first presented a sequence of digits (high or low working memory load) which they had to memorize. Next, subjects performed a handful of selective attention trials, in which they had to classify the names as belonging to either category. Finally, working memory was tested by asking subjects to reproduce the stored digit sequence. The crucial test was whether the size of the interference effect would interact with working memory load. The results showed, first, a significant interference effect: RTs to incongruent name/face combinations were larger than to congruent ones. Second, and more importantly, the interference effect was larger in the high working memory-load condition than in the low working memory-load condition. Moreover, this pattern of results was mirrored in their fMRI-data. More specifically, cortical areas responsible for visual face processing, such as the fusiform gyrus, were more strongly activated when a distractor face stimulus was shown under conditions of high working memory load than low working memory load. Thus, de Fockert, *et al.* (2001) found convincing evidence for their thesis that working memory is needed for the selective attention system to function properly.

In this paper, we used a dual task methodology that closely resembles the design used by de Fockert, *et al.* (2001), but with different working memory and selective attention stimuli. We used working memory stimuli in which we varied the working memory load from two to four items (instead of the two levels of de Fockert, *et al.*, 2001), so that we could test whether there would be a monotonic increase in distractor interference with increasing working memory load. We also used different selective attention stimuli than faces and names because these stimuli have the potential drawback that they rely heavily on activations stored in long-term memory. Each subject in our experiment was tested using two selective attention tasks that make use of elementary visual symbols. The first task (the colour Stroop task, described below) accesses the verbal system; the second task (the Simon task) accesses the visuospatial system. It would be interesting to see to what extent interference effects in both tasks and their interaction with working memory lead to similar conclusions. For ease of exposure, we first describe the working memory task and the two selective attention tasks in isolation, although in the actual experiment the tasks were combined in the dual-task paradigm.

Working Memory Task: Corsi Blocks

We tested working memory by employing a computerized version of the Corsi blocks task. In the original version of this visuospatial working memory task an experimenter (or tester) points to a number of blocks put on a table in a specific order, and the subject simply has to reproduce this sequence again by pointing. Subjects thus have to store the positions of the blocks and the order in which they were pointed at (see Fischer, 2001, for a review of this task). In the computerized version, the blocks appear one by one on a screen, and the subject is instructed to reproduce the original sequence by touching the positions on a touch sensitive monitor (touch screen). This version of this Corsi blocks task permits us to vary working memory load in a continuous (discrete) fashion. In our task, subjects had to store the positions and sequences of two, three, or four blocks, resulting in working memory loads of two, three, or four items, respectively.

Selective Attention: Stroop Task

The colour Stroop task (Stroop, 1935) is a well known task that, in various guises, has found its way into the experimental psychologists' laboratory and the neuropsychologists' test battery (for a review, see MacLeod, 1991). In the original version subjects had to read aloud coloured items printed on two cards. The so-called control card consisted of 100 rectangles, each printed in one of the colors red, blue, green, brown, or purple. The so-called experimental card consisted of 100 words, each designating one of the words "red," "blue," "green," "brown," or "purple." The words were also printed in one of the five colored fonts. In this card word color and ink color never matched, i.e., they were always incongruent. When asked to read aloud the ink colors, subjects experience difficulties suppressing the word meaning. This results in higher RTs and more errors for the experimental card than for the control card.

We employed the computerized version of the color Stroop task, whereby subjects did not have to name the colors (as in the original version) but whereby they had to classify Stroop color words by pressing one of two keys. This allows us to measure the RTs on a trial-by-trial basis. In our task, we employed four colors, instead of the original five. We used the words "red," "yellow," "green," and "blue," each printed in a red, yellow, green, or blue font. In half the cases word color and font color matched or were congruent, e.g., the word "yellow" shown in a yellow font; in the other half of the cases word color and font color did not match, i.e., they were incongruent so the word "red" was shown in a blue font. Subjects had to respond to font color and were to ignore word meaning. We expected that for incongruent stimuli, a response conflict would emerge because subjects would have to suppress automatic responding to the word. This will elevate RTs, relative to the congruent condition.

Selective Attention: Simon Task

The Simon task (sometimes called the spatial conflict task) exploits the fact that subjects have a strong tendency to respond to the position of an abrupt visual or auditory event (either an onset or an offset). In the original version (Simon & Rudell, 1967), subjects had to respond to the words "right" or "left" by pressing, respectively, the right or left response button. The word was randomly presented to the right or left ear, but the ear stimulated had to be ignored. It appeared that subjects responded somewhat faster when the (task irrelevant) ear stimulated and response side spatially corresponded than when they were mismatched. The response conflict that arises from the mismatch has to be resolved, resulting in slower RTs. In our experiment, we adopted a visuospatial version of the Simon task, wherein subjects had to react to the color of a visual symbol while ignoring its (task irrelevant) left or right position. Also in this design, we expect somewhat faster RTs when stimulus location and response side correspond (see Simon, 1990, for a review of the Simon effect). The reason for including the Simon task is to test whether putative interference effects with our working memory task are somehow dependent on the sensory modality in which the selective attention system operates (visuospatial in the Simon task, and verbal in the Stroop task).

The Dual Task

The experiment consisted of two dual-task sessions, one session in which the Corsi task was combined with the Stroop task, and one part in which the Corsi task was combined with the Simon task. The experimental design closely resembled the de Fockert, *et al.* design (2001). In general, subjects first received a number of Corsi blocks which they had to memorize and which then created a certain working memory load. The number of to-be-stored blocks was either two (Low working memory load), three (Intermediate working memory load), or four (High working memory load). Directly afterwards, subjects were to respond to a variable (between two and four) selective attention stimuli. During responding subjects had to try to maintain the Corsi blocks in working memory. After the last selective attention trial, subjects finally had to reproduce the sequence of Corsi blocks.

Hypotheses

First, we expected an interference effect in both interference tasks. Thus, we predicted both in the Stroop task and in the Simon task slower responding in the incongruent than the congruent condition. Second, we expected that as working memory load increased, i.e., more blocks had to be stored, the number of errors would also increase. This would imply that our working memory manipulation was effective (Fischer, 2001). Third, we expected an interaction between working memory load and response interference. According to de Fockert, *et al.* (2001), the *greater* the load on working memory, the *less* capable the selective attention system is in suppressing task-irrelevant information. With respect to our task, the selective attention system is needed to suppress location information in the Simon task and word-meaning information in the Stroop task. We expected that the process of suppressing this information would be less efficient the more working memory is occupied, hence the RT difference between congruent and incongruent trials would be exaggerated. In short, the size of the interference effect was predicted to increase with increasing working memory load. Finally, we tested the complementary hypothesis, that suppressing task-irrelevant information reduces the probability of correct working memory recall.

METHOD

Subjects

Twenty-nine volunteers participated (*M* age = 26 yr., range = 19 to 44). The subjects were offered a coupon to redeem for a CD of their choice.

Materials

All tasks were performed in a soundproof room. Each subject was seated in a comfortable chair in front of a 15-in. touch screen monitor on which all stimuli were presented. Directly in front of the subject were four response buttons, arranged in a square. The distance between the left and right buttons was 49 cm, the distance between the proximal and distal buttons was 10 cm. The two proximal buttons were designated the home keys; the two distal buttons were the response keys. Throughout the experiment, both home keys had to be kept pressed, except when a response had to be given, which could involve pressing one of the ipsilateral response buttons, or touching the locations of the touch screen. The release time of the home keys was the measure of RT.

We now describe the working memory task and the selective attention tasks in isolation, and next we will describe the dual-task version. The tasks were practiced in isolation, but the actual experiment consisted of the dual task.

The Corsi Working Memory Task

Working memory load was manipulated by administering a computerized version of the Corsi blocks task. Subjects were presented an image of nine blocks on the screen. Each block measured 4 × 4 cm. The blocks were shown against a dark background in a random configuration. The relative position of the nine blocks remained fixed throughout the experiment and was the same for all subjects. Eight blocks were white, the ninth block was red, and its position had to be memorized. The block pattern remained on the screen for 1 sec., after which it was replaced by the same nine blocks, but now a different block was colored red, and the remaining eight blocks were white (including the previously red block). This was repeated for two, three, or four red blocks, which gave the impression of a red block occupying different positions in succession on the screen. Within a sequence the red block never occupied the same position twice.

Subjects were instructed to memorize the positions the red block had occupied, and the particular order in which they were shown. After the last block all nine blocks turned white, and subjects had to reproduce the memorized sequence by touching the white blocks in the same order as the red block. No emphasis was put on speed. The computer registered the locations and response times of the presses on the touch screen.

Selective Attention Tasks

Stroop stimuli were the Dutch equivalents of the words 'red' (*rood*), 'yellow' (*geel*), 'green' (*groen*), and 'blue' (*blauw*), each shown in any of these four colors. This leads to 16 different combinations, of which four are congruent and 12 are incongruent. In the actual experiment, the number of congruent and incongruent stimuli was set to be equal. Subjects were instructed to release the left home key and press the left response key when the color of the word was either red or green and to release the right home key and press the right response key when its color was yellow or blue and to ignore the meaning of the word.

The words were printed in capitals and measured 4.5 by 1 cm. Stroop words were shown in the middle of the screen for 800 msec.

In the Simon task, a white fixation cross appeared in the middle of the screen, which was flanked by two circles with a diameter of 1.5 cm each. The circles appeared 7.5 cm left and right of the cross. One circle was colored blue or green; the other constituted a white outline. Subjects had to release the left home key and press the left response key in response to the green circle and to release the right home key and press the right response key to the blue circle. Subjects had to ignore the location of the stimulus. Stimulus color and stimulus location were uncorrelated. Simon stimuli were shown for 800 msec.

In both tasks, subjects were asked to respond as quickly and as accurately as possible.

Dual Tasks

The experiment consisted of a dual task session in which the Stroop task was combined with the Corsi blocks task, and a session in which the Simon task was combined with the Corsi blocks task. Each session was subdivided in three trial sets, in which either two, three, or four Corsi blocks had to be stored (working memory load = 2, 3, or 4). In both sessions, the order of presentation of the sets was randomized. Each set consisted of 16 series of Corsi blocks combined with selective attention trials. Within each series, subjects first had to memorize a number of Corsi blocks (which remained constant within a particular set), followed by a variable number of selective attention stimuli to which they had to respond. At the end of each series there was first a 3-sec. interval, after which nine white blocks were shown. Subjects had to reproduce the original sequence of Corsi blocks shown at the beginning of the series by slightly touching the relevant positions on the touchscreen.

The number of selective attention trials within a series could randomly vary between two and four. Within a particular set, there were five series of two selective attention trials, six series of three selective attention trials, and five series of four selective attention trials. This leads to a total of 48 selective attention (24 congruent and 24 incongruent) trials within a set. The 16 series were presented in a random order. Since there were three sets of trials, the total number of Simon trials was 144, as was the number of Stroop trials.

Fig. 1 shows an example of a series of Corsi + Stroop trials.

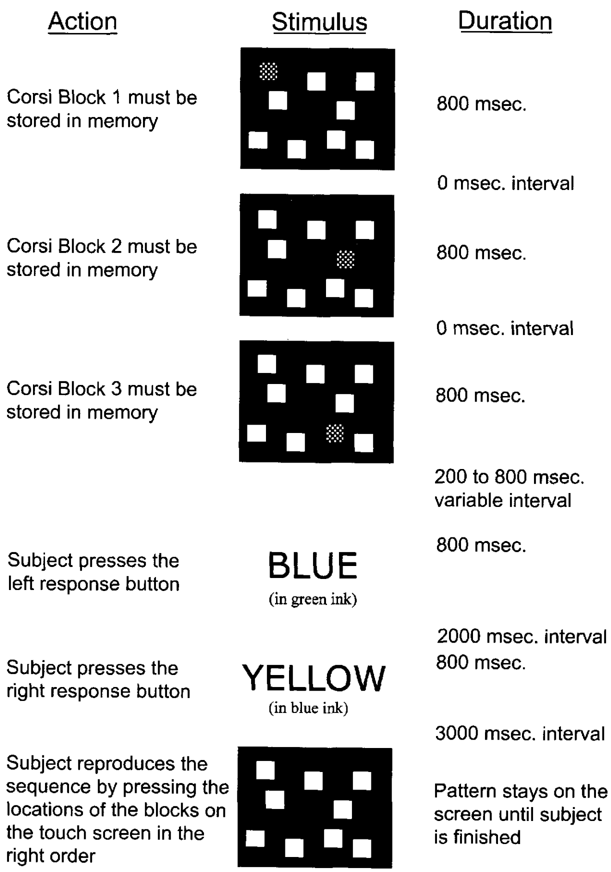

FIG. 1. Example of a series consisting of three Corsi blocks, followed by two Stroop trials. Subjects had to memorize the locations of the blocks and next respond to the interference trials. The left column shows the actions the subject has to take in response to the events; the middle column shows the visual symbols shown on the screen, and the right column shows the durations of the respective events. In the actual experiment the Corsi blocks were red, and the Stroop words were shown in different ink colors.

Prior to the experiment, subjects were given a few practice trials with the individual subtasks (Corsi, Stroop, and Simon), followed by a few trials in the dual task version.

Results

We only analyzed RTs to the Stroop and Simon trials if they fell in the range 150 to 1500 msec. and if a correct response was given. In addition, only RTs were included in the analysis if within a series all Corsi blocks were reproduced correctly. This criterion ensured us that, at those selective attention trials, working memory was effectively occupied. A preliminary analysis indicated some participants had an extremely high error rate at the Corsi blocks, especially at the highest load. We decided to include only participants who had at least eight out of 16 series (50%) correct at each of the three working memory loads. To this end, we had to exclude the data of three participants on the Stroop task and the data of five participants on the Simon task from the analyses.

Our analyses showed first that error rate increased with increasing working memory load. For the Stroop task we found that at Low working memory load 93.5% of the Corsi series were correctly reproduced, at Intermediate working memory load 90.0%, and at High working memory load 77.7%. For the Simon task we found a comparable accuracy profile: 92.0%, 92.9%, and 72.3%, respectively.

Dual Task: Corsi + Stroop

A 2 × 3 analysis of variance was performed on the RTs, with stimulus type (congruent vs incongruent) and working memory load (two, three, or four Corsi blocks) as factors. First, the main effect of stimulus type ($F_{1,25} = 20.68$, $p < .001$, $\eta_p^2 = .453$) was due to a 29-msec. RT advantage for congruent trials over incongruent ones (649 vs 678 msec., respectively). There was no effect of working memory load, but working memory load interacted with stimulus type ($F_{2,50} = 7.90$, $p < .001$, $\eta_p^2 = .240$). These effects are shown in Fig. 2 wherein one can see the interference effect is small at Low and Intermediate working memory loads (15 msec. and 18 msec., respectively) but substantial at High working memory load (53 msec.). A *post hoc* Bonferroni test showed that the interference effect was only significant at High working memory load and not at the lower loads.

Dual Task: Corsi + Simon

We performed the same analysis of variance on the RTs. There was a main effect of stimulus type ($F_{1,23} = 33.05$, $p < .001$, $\eta_p^2 = .590$), which signalled a 33-msec. RT advantage for congruent trials over incongruent ones (584 vs 617 msec., respectively). The main effect of working memory load was not significant, but working memory load interacted with stimulus type ($F_{2,46} =$

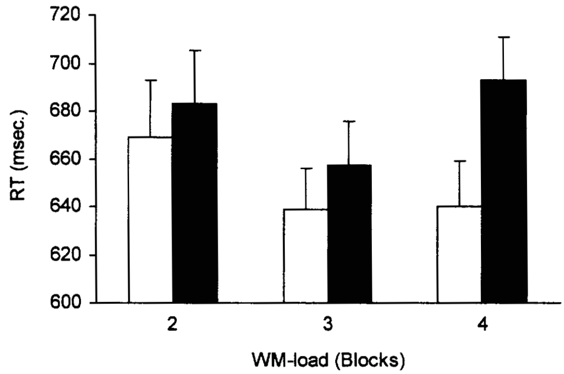

FIG. 2. Mean RTs (msec.) and standard error bars for the Stroop and Corsi dual task as a function of stimulus type [congruent (□) or incongruent (■)] and working memory load (two, three, or four blocks)

11.05, $p<.001$, $\eta_p^2=.324$). In Fig. 3, it can be seen that the interference effect is largest at Low working memory (50 msec.), smaller at High working memory load (41 msec.), and smallest at Intermediate working memory load (9 msec.). A *post hoc* test indicated the interference effect was significant at Low and High working memory loads but not at the Intermediate load.

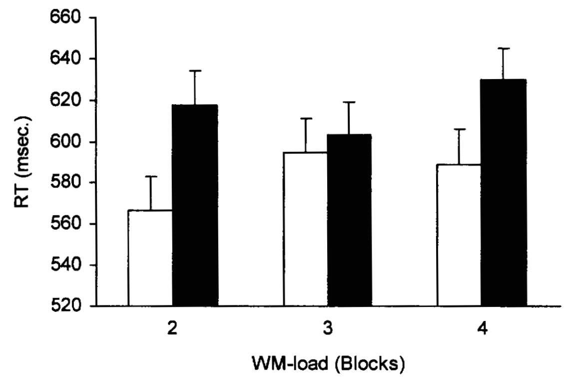

FIG. 3. Mean RTs (msec.) and standard error bars for the Simon and Corsi dual task as a function of stimulus type [congruent (□) or incongruent (■)] and working memory load (two, three, or four blocks)

Influence of Stimulus Type on Memory Performance

In the previous analyses, we established that there is weak evidence for an influence of working memory load on performance on a selective attention task. However, the reverse could also be true, in that the congruency of selective attention stimuli within a series influences the workings of the working memory system. More specifically, if within a given series the number of incongruent trials happens to be high, then resolving the response conflict on these trials may somehow put a strain on the working memory system, which in turn may reduce the probability of correct recall of the pattern of Corsi blocks. To this end, we first obtained for each series the percentage of incongruent trials. For example, in the series shown in Fig. 1 there is one congruent and one incongruent Stroop trial, resulting in an incongruency percentage of 50%. This percentage was only calculated for trials which were correct and for which the RTs were in the range of 150 to 1500 msec. So if in the above example a subject made one error in a congruent trial, the incongruency percentage for this series would now become 100%. Next, we calculated for each subject the mean incongruency percentage separately for Corsi series that were reproduced correctly and for series that were reproduced incorrectly. Finally, we performed a paired t test on the incongruency percentages for the Stroop task and the Simon task. For the Stroop task the mean incongruency percentage for incorrect Corsi series was 49.2%, and for the correct series it was 47.9%. This difference was not significant ($t_{24} = .33$, ns). However, the Simon task did yield a significant effect in the expected direction: the mean incongruency percentage for incorrect Corsi series was 56.0%, and for the correct series it was 51.1% ($t_{21} = 2.06$, $p < .05$). Thus, for the Simon task a relatively large percentage of incongruent trials within a series tends to reduce working memory performance.

Discussion

Using two dual tasks we have tried to find evidence for de Fockert, *et al.*'s hypothesis (2001) that working memory is needed to minimize possible response interference caused by task-irrelevant information. We thus expected that as working memory load increases, the selective attention system would be less capable of filtering irrelevant information, so an increase in response interference in both tasks would be observed.

First, we found that as working memory load increased subjects made more errors in reproducing the original sequences. It thus seems that the working-memory manipulation was effective. Second, we found for both the Stroop task and the Simon task significant response interference: RTs were generally slower to incongruent trials than to congruent ones. Our main prediction involved an interaction between the working memory load and the amount of response interference. We found some evidence for this thesis with our Stroop task, in that Stroop interference was largest with the High working memory-load (four blocks in memory) but virtually absent at the lower loads (two or three blocks). The pattern of results was, however, more erratic with the Simon task, in that response interference was only present for the High and Low working memory-load but not for the Intermediate working memory load. At present we do not have an explanation for this peculiar pattern. Our final outcome was that working memory performance was somewhat worse when subjects had just encountered a high percentage of incongruent Simon trials. However, this was not found for the Stroop task.

In sum, we have found weak evidence for the notion that working memory and selective attention are intertwined systems. A possible reason for the absence of strong effects might be due to the nature of the selective attention tasks used. It might simply be that our tasks were relatively easy to perform and hence hardly taxed the working memory system. Evidence for the notion that higher working memory load resulted in larger response interference was found only for the Stroop task and not for the arguably simpler Simon task. The selective attention task used by de Fockert, *et al.* (2001), in contrast, yielded substantial interference effects, and this arguably results from the fact that subjects were confronted with relatively demanding stimuli (faces and names of famous persons).

An unresolved question is why working memory and selective attention would interact in the first place. First, working memory and selective attention could be just different labels for the same underlying construct. Psychological constructs are notoriously difficult to define (e.g., Uttal, 2001), and this could lead to a plethora of labels used to describe empirical patterns. Alternatively, the working memory system and selective attention system could be indeed separate, but they both may make use of a limited pool of cognitive resources. As has been pointed out by Sanders (e.g., 1983), information processing not only involves a computational component but also an energetic component, e.g., arousal. If two distinct processes compete for the same limited energetic resource, then performance on the processes will be negatively correlated. Further experiments, using the dual task methodology, may find ways to distinguish between these two scenarios.

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